REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0034

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE		3. DATES COVERED *(From - To)*
	Final Report		Nov 15, 00 - Nov 14, 03

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Time Sensitive Control of Aerospace Operations	
	5b. GRANT NUMBER
	F49620-01-1-0008
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Dr. Alexander H. Levis	
20040130 068	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
C3I Center, MSN 4B5 George Mason University Fairfax, VA 22030	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
Department of the Air Force Air Force Office of Scientific Research	4015 Wilson Blvd. Arlington, VA 22203-1954	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release. Distribution unlimited

13. SUPPLEMENTARY NOTES
DODAAD CODE: 97668
AFOSR Program Manager: Lt. Col. Juan R. Vasquez

14. ABSTRACT
Task 1: The theoretical objectives of the task have been achieved; the approach can now handle MTMF-type I systems with the help of hierarchical Point graphs, developed as part of the research initiative. The software implementation of the methodology, called TEMPER, incorporates some of the new features; however, a comprehensive revision of the tool is required to satisfy the objectives stated. The provision for point-interval representation of time, an expressive language for specifying temporal aspects, both qualitative and quantitative, and a powerful inference engine makes the approach a potential tool for carrying out critical path analysis (i.e., CPM, PERT) for managing temporal aspects of large-scale projects. The approach is being extended to incorporate such an analysis tool in it. Task 2: The Point-interval Logic has been successfully extended and used for handling both temporal and spatial specifications of a system under investigation. The logic, however, treats the two types of specifications independent of each other. A further investigation is tinder way for integrating the two applications into a single formalism. A unified approach will not only be able to handle the temporal and spatial constraints as they are handled by the current approaches, but will also be able to capture 'motion' in space. The integration is expected to pave the way for addressing the planning/re-planning problem(s).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Alexander H. Levis
					19b. TELEPHONE NUMBER *(Include area code)* 703-993-1712

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AFOSR FINAL PRODUCTIVITY REPORT

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Project Title: Time Sensitive Control of Aerospace Operations

1. STATEMENT OF WORK

The following task statements describe the research under this contract:

Task 1: Extend the capability of the Temporal Programmer, TEMPER, to address the general case for systems with multiple time lines with multiple futures (MTMF)

A multiple time lines with multiple futures (MTMF) system is characterized either by a single set of events with associated multiple time lines each yielding a different future (type 1) or by multiple set of events with different single/multiple time sequences each representing a total world-history (type 2). In addition to enhanced capabilities in terms of the type of temporal systems, the tool will have a web-based interface to facilitate collaborative planning and re-planning in the time domain.

Task 2: Integrate Temporal and Spatial Paradigms

The dynamic planning and re-planning problems require satisfaction of two types of constraints, namely temporal and spatial. The time-sensitive aspect requires a planner to sequence time intervals (points) associated with mission activities without violating any of the system specifications, given a priori. The spatial aspect, on the other hand, needs to look at the availability of the physical resources capable of handling the required task list. The challenge here is to integrate both these constraints in a single analytical formulation of the problem and devise an engine that can

    (i) model the two aspects using a single integrated formalism,

    (ii) validate the feasibility of all types of constraints, and

    (iii) help generate a feasible plan, given additional mission requirements.

Task 3: Generate Time Phased Plans using Occurrence Graph analysis of a Colored Petri net model consisting of a physical layer, a temporal layer, and a collaboration layer.

The collaborative generation of feasible time phased plans, either at the initial planning stage or during dynamic battle control, which is based on changes in the environment, changes in tasks to be performed or changes in resources available, can be formulated as a three layer problem using a physical layer, a temporal layer, and a collaboration layer. There is a set of tasks, which must be performed to accomplish a goal (e.g., execute a mission or complete an operation) and a set of resources, which can be used to execute the tasks. At the physical layer, the relationship between tasks and resources capable of executing the tasks is specified along with the resource capabilities (time to execute given tasks, multitasking capability, etc.) At the temporal layer, the sequencing constraints between tasks, required task completion times, etc., are modeled using a temporal logic model such as the Point-Interval temporal Logic (PITL) of Zaidi. At the collaboration layer, the merging of temporal requirements and physical resource constraints to determine the feasible time phased plan is accomplished so that both the temporal constraints and the resource constraints are satisfied. In this task, the collaboration will be modeled in the form of Colored Petri nets and analyzed by occurrence graph analysis of the nets.

Task 4: Document the results of the research in the form of theses, technical reports, and journal articles. Present the results of the work in technical meetings. Submit progress and other reports to AFOSR in accordance with grant requirements.

2. STATUS OF EFFORT

This section presents a brief overview of the status of the research findings and the progress made on the proposed tasks during the last couple of years.

The tasks in this research are motivated by an effort to integrate temporal and spatial aspects of a large-scale discrete event system (DES) for dynamic control (i.e., planning and re-planning) purposes. As stated under Task 2, the dynamic planning and re-planning problems require satisfaction of two types of constraints, namely temporal and spatial, and the challenge here is to integrate both these constraints in a single analytical formulation of the problem. In addition, the constraints may not be all quantitatively specified; therefore, there is a further need to have provisions for both quantitative and qualitative constraint-handling in this formulation. The results, achieved so far, have successfully solved some of the issues and pose both challenges and promise in resolving others.

The dynamic control of Discrete-Event Systems (DES) often requires revising a produced temporal model during and/or after system specification phase, e.g., the constraints or system/mission requirements may change during or before a plan's execution. The approach developed in this research [Zaidi and Rauf, 2002] uses a multi-layered Point Graph (PG) structure to keep the input specifications in the lowest layer of a PG. The approach enables the qualitative and quantitative information available to the software application (TEMPER) developed under this grant is processed and kept at a higher layer in the PG. The inference engine works at the higher layer to answer queries and infer new temporal relations; however, a change in the inputs is processed at the lowest layer and its *effects* are propagated upwards. The effected parts of the PG determine the kind of change required of TEMPER to accommodate the change.

The underlying point-interval formalism presented in [Zaidi, 1999, 2000; Zaidi and Levis, 2001; Rauf and Zaidi, 2002] has been extended [Hussain and Zaidi, 2002], to model the spatial information in a 1-dimensional case, with temporal components of the lexicon replaced by their spatial counterparts. The logic, however, is extended to incorporate *orientation* aspects in spatial reasoning. The PG formalism is shown to handle the orientation aspect with the help of a new set of axioms in the logic. The spatial version of TEMPER has been developed and is called SPINE (Spatial Inference Engine.) A recent paper [Zaidi et al., 2003] builds upon the logic proposed for reasoning over spatial relations in one dimension, forming spatial relations for objects in 2-D. A point, a vertical line, a horizontal line, and a rectangle, are taken as primitive spatial objects in this approach. The spatial specifications are input by identifying the objects, their shape characteristics, and known spatial relationships among objects. The representation of an object in space is determined by the projections of the object on both the x- and y-axes. The graph based representation of PGs is used to model the x and y projections of the objects in space. The graph-based spatial inference engine (SPINE) identifies spatial ambiguities and errors (if present) in the system's specifications, infers new spatial relations among objects' x and y projections, exactly like its temporal counterpart with an added capability of orientation. A second set of axioms is added in SPINE to enhance its inference capabilities for 2-dimensional case. The new set of axioms takes the SPINE inferences about the objects' x and y projections and infers their qualitative spatial relationships in space.

The use of a single formalism, Point Interval Logic and Point Graphs (PG), for both temporal and spatial knowledge representation and reasoning has provided a unifying basis for the two types of information and their processing for dynamic control of aerospace operations. The ex-

pectation is to use the point-interval formalism as the underlying analytical model for reasoning about space and time in a unified manner, both qualitatively and quantitatively. The handling of motion in space is an important challenge that needs to be tackled before a real attempt can be made on control of a dynamic discrete-event system. It is expected that the integration of the two aspects—spatial and temporal—holds the promise for such a capability to be acquired. The current effort is focused on extending the 2D PISL to a three dimensional case, where time is the third dimension.

3. ACCOMPLISHMENTS/NEW FINDINGS

Task 1: The theoretical objectives of the task have been achieved; the approach can now handle MTMF-type I systems with the help of hierarchical Point graphs, developed as part of the research initiative. The software implementation of the methodology, called TEMPER, incorporates some of the new features; however, a comprehensive revision of the tool is required to satisfy the objectives stated. The provision for point-interval representation of time, an expressive language for specifying temporal aspects, both qualitative and quantitative, and a powerful inference engine makes the approach a potential tool for carrying out critical path analysis (i.e., CPM, PERT) for managing temporal aspects of large-scale projects. The approach is being extended to incorporate such an analysis tool in it.

Task 2: The Point-Interval Logic has been successfully extended and used for handling both temporal and spatial specifications of a system under investigation. The logic, however, treats the two types of specifications independent of each other. A further investigation is under way for integrating the two applications into a single formalism. A unified approach will not only be able to handle the temporal and spatial constraints as they are handled by the current approaches, but will also be able to capture 'motion' in space. The integration is expected to pave the way for addressing the planning/re-planning problem(s).

Task 3: The temporal engine has been applied to sequence events of interest in an Influence net, modeled with the help of CAT software, for the problem of planning courses of actions (COA). The sequencing is found useful in determining the possible causes of an event under consideration. The application of TEMPER is expected to provide better algorithms for re-planning COAs, especially when evidences regarding events in the Influence net arrive at the time of plan execution. A forthcoming paper/technical report will describe the approach in detail. A revision capability has also been introduced in the temporal formalism for addressing the change in temporal specifications during the time of plan execution. The revision capability is also expected to help enhance TEMPER for handling MTMF, type II, systems. The inference problem in a MTMF, type II, system has been proved to be NP-complete. The revision algorithm, used with heuristics for its application, may help develop faster (on average) algorithm(s) for the problem. The issue, being outside the scope of current research, may be addressed by some future effort.

4. PERSONNEL SUPPORTED

Faculty:
    Prof. Alexander H. Levis (on leave)
    Dr. Lee W. Wagenhals (supported)
    Dr. Abbas K. Zaidi (supported)

Graduate Students (Ph.D.)
    Mr. Sajjad Haider (supported)

5. PUBLICATIONS (During this reporting period)

1. I. Rauf and A. K. Zaidi, "A Temporal Programmer for Revising Temporal Models of Discrete-Event Systems," in *Proc. of 2002 IEEE International Conference on Systems, Man, and Cybernetics*, Hemmamat, Tunisia, 6-9 October 2002.

2. A. K. Zaidi, "Qualitative and Quantitative Spatiotemporal Knowledge Representation and Reasoning Using Point Graphs." Notes of Workshop on Spatial and Temporal Reasoning, 18th International Joint Conference on Artificial Intelligence, Acapulco, Mexico., Aug 2003

3. A. K. Zaidi, Kazim H. Rizvi, and Sajjad Hussain, "On Spatial Modeling of Discrete Event Systems Using Point-Interval Logic". To appear in the proc. of *IEEE SMC 2003*, Washington DC, USA, October, 2003.

6. INTERACTIONS/TRANSITIONS 10/1/02 - 9/30/03

a. Participation in Conferences, Meetings:

1. Paper in the "2002 IEEE International Conference on Systems, Man, and Cybernetics," Hemmamat, Tunisia, 6-9 October 2002.

2. Presentation at the "AFOSR Optimization and Discrete Mathematics Program Review," Estes Park, Colorado, 27-28 May 2003.

3. The following papers were given at the 8th International Command and Control Research and Technology Symposium, 17-19 June 2003, National Defense University, Washington, DC:

    a. L. W. Wagenhals and L. K. Wentz, "New Effects-Based Operations Models in War Games."

    b. L. W. Wagenhals, A. H. Levis, and Maris "Buster" McCrabb, "Effects-Based Operations: A Historical Perspective for a Way Ahead".

    c. L. K. Wentz and L. W. Wagenhals, "Information Operations in Effects Based Operations: Some Observations."

b. Invited Presentations

1. Workshop on Spatial and Temporal Reasoning, 18th International Joint Conference on Artificial Intelligence, Acapulco, Mexico, Aug 2003. (Paper submitted, and published in the notes of the meeting, but couldn't be presented.)

c. Consultative and Advisory Functions

1. GMU participated in AFRL/IF planning for a demonstration of EBO capability during the Air Force JEFX –04 in July 2004. GMU's experience in the Global 2000 and 2001 war games and the Millennium Challenge 02 has been invaluable in helping AFRL plan for their participation in JEFX-04.

d. Transitions:

1. Throughout the course of this grant, GMU collaborated extensively with Dr. John Lemmer of the Air Force Research Laboratory (Information Directorate, Rome Site). Dr. Lemmer is the principal developer of the Campaign Assessment Tool (CAT). He provided the source code for CAT to GMU. In return, GMU provided new algorithms that have been incorporated in CAT. CAT will be a major component of the AFRL ATD on Effects Based Operations and will be central to the AFRL EBO initiative in JEFX-04.

2. This technology has been transitioned to (a) the Naval War College's capstone war game Global 2001; (b) the information assurance area through the National Institute of Justice's program for secure information systems; (c) the Air Force Studies and Analysis Agency in support of Operation Enduring Freedom; and (d) the JFCOM Millennium Challenge 02 experiment.

7. NEW DISCOVERIES, INVENTIONS, PATENT DISCLOSURES:

None

8. HONORS/AWARDS

Dr. Wagenhals and Dr. Levis received the best paper award at the 7th Command and Control Research and Technology Symposium in Monterey, CA in June 2002.

Previous Lifetime Honors:

Prof. Levis is a Fellow of IEEE (1987);
Prof. Levis is a Fellow of AAAS (1991)
Dr. Levis received the Exceptional Civilian Service Medal, Dept. of the Air Force (1994)
Prof. Levis was awarded the IEEE Third Millennium Medal for "outstanding achievements and contributions" (2000)

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[Zaidi et al., 2003] A. K. Zaidi, Kazim H. Rizvi, and Sajjad Hussain, "On Spatial Modeling of Discrete Event Systems Using Point-Interval Logic". Submitted for *IEEE SMC 2003*, Washington DC, USA, October, 2003.